Results of the Sequestration Workshop

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Overview

In response to increasing concerns about global climate change, there is a heightened interest in cost-effective options for mitigating greenhouse gas emissions. Carbon sequestration offers the only set of mitigation options that will allow us to continued using fossil fuels while greatly reducing their net emissions of greenhouse gases. However, much work must be done to determine the technical feasibility, economic viability, and environmental soundness of carbon sequestration.

The Massachusetts Institute of Technology (MIT) Energy Laboratory organized and hosted a *Stakeholders' Workshop on Carbon Sequestration* on June 22-23, 1998 in Cambridge, MA. This event is part of a larger Federal Energy Technology Center (FETC) effort aimed at soliciting input from industry and academic stakeholders and forming partnerships. Specific objectives for this workshop included:

- to update stakeholders on the latest developments concerning carbon sequestration
- to solicit stakeholder input on research and development priorities for carbon sequestration
- to identify possible industry-government-university partnerships

There were 118 participants in this meeting -- 46 from industry, 36 from academia, and 36 from government. The first half of the meeting consisted of plenary sessions, where speakers described the context for the meeting, including the political, economic, and technology aspects. Then, the workshop was divided into three breakout sessions organized by industry groups (i.e., coal, electricity, and oil & gas) to solicit stakeholder feedback and explore possible partnerships. A final plenary session reported on the breakout sessions. The meeting agenda and breakout session agenda are attached.

Plenary Sessions

The *Keynote Address* was given by Rita Bajura, Director, FETC. Some highlights of her talk:

> This is the first time DOE has requested stakeholder input on carbon sequestration. About 80% of the world's anthropogenic carbon dioxide emissions comes from energy uses. The US uses 94 quads of energy (10^{15} Btus) out of 420 quads for the entire world. Over 85% of US energy comes from fossil fuels. Population growth is expected to continue in the developing countries raising the world population to the order of 10 billion by 2100 from 5.9 billion today. Energy use will likely triple in that time frame.
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> The technical options for controlling CO_2 emissions are limited to decarbonization of fuel, increased efficiency, or carbon sequestration. While renewables will likely increase, they are not likely to provide any substantial substitute for the major fossil fuels. Technology improvements leading to increased efficiency is a no regrets approach to reducing CO_2 emissions. However, if the science indicates that stabilization of the CO_2 level is needed to avoid climate impacts, sequestration will be needed.
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> The Vision 21 coal-fired power plant being developed by DOE will reduce coal based CO_2 emissions to levels near today's natural gas combined cycle power plants. However, what would be desirable is to have a "zero emissions" coal plant. This means that there would be essentially no air, water, or surface emissions.
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> Carbon sequestration is feasible. There are several plants already recovering CO_2 for various uses. DOE has initiated several programs to begin to increase our understanding of this problem. Some $12 million has been proposed for FY99 funding. This program will be with us for many years to come. The stakeholder input from this workshop will be used to help set DOE policy and programs for the future.

Next, Professor Henry (Jake) Jacoby of MIT discussed *Technology's Role in Carbon Management*. Professor Jacoby is a co-director of MIT's Joint Program on the Science and Technology of Global Climate Change. Highlight's of his talk are:

> Technology is not a magic bullet, but without it there is no hope. There will be many pitfalls along the way to a coherent technology strategy. Sinks present an opportunity, and a danger, to the Climate treaty. Sequestration has to compete with these economically or we won't see it.
>
> As an example of the difficulty of controlling CO_2 emissions, an MIT model was used to examine impacts of various scenarios. The model takes into account 12 regions of the world and includes trade flows and GDP activities, as well as energy use. If one assumes that a target stabilization level of 550 ppm of CO_2 is deemed desirable, then carbon intensity of the world would have to be reduced by more than 50% to 0.8 tons per capita. The OECD is currently 3.6 tons per capita, while the US is about 6.0 tons per capita. To accomplish this all with the just the Annex I countries would require negative emissions -- an impossibility. The developing countries have other priorities. In order to get them involved, we are probably

going to have to pay them. The cost of this is huge compared to traditional foreign aid programs.

The notion of "conventional" oil, as opposed to "non-conventional" is a myth. Heavy oils (once considered non-conventional) are already being produced today. These sources (including shale, clathrates, etc.) are roughly 6 - 7 times what is termed "conventional" oil. Thus, there is a minimum
of 100 years of fossil fuels.

The Kyoto process is seen as a short term political goal as opposed to a long term solution. The $6.3 billion is to force technologies in the short term to meet a political target. Aside from credible price incentives and direct regulation, government has limited ability to impact the problem, especially with the diversions to short term political impacts. R&D is one of the few tools that can help. A clear eyed assessment is needed to get to a long term solution.

The second plenary session started with Howard Herzog of MIT giving an *Overview of Sequestration Technologies*. Highlights include:

Although the US has not ratified the Kyoto protocol, it has agreed to the Framework Convention on Climate Change, which has as its objective the stabilization of CO_2 in the atmosphere. In doing a general mass balance, the input to the atmosphere has to equal the output from the atmosphere to achieve stabilization. While most other mitigation strategies try to reduce the input term, sequestration tries to maximize the output term. This allows continued use of our abundant fossil energy resources. Because of the limited number of strategies for GHG control, carbon sequestration should be pursued for any long term mitigation solution. The key research challenges are to identify options that are technologically feasible, economically viable, and environmentally sound.

Sinks for sequestration include geologic, oceanic, terrestrial, or conversion. For geologic formations, the carbon is essentially returned to the ground. These could be deep saline aquifers, depleted oil & gas reservoirs, active oil & gas fields, and unmineable coal seams. Current technology can capture CO_2 from point sources for $40 - 60/ton CO_2. This cost could be reduced 50% or more based upon new technology. The oceans are the largest sink of CO_2. Most of the carbon emitted to the atmosphere will end up in the ocean, but the process is slow (maybe 1000 years). It would be desirable to enhance the uptake of CO_2. Possible ocean strategies include direct injection, iron fertilization, and ocean farming. The land also has uptake that could be enhanced (see speakers below). Advanced chemical and biological conversion processes are perhaps the most difficult to achieve. Industrial processes, microalgae, carbonate materials, and conversion to fuels are being considered.

The second paper in this plenary session concerned *The Technological Response in Norway*. It was given by Olav Falk-Pedersen of Kværner Oil & Gas in Norway. Key points included:

In Norway, there has been a CO_2 tax since 1991. In 1996, the CO_2 tax for offshore applications amounted to $53/tonne CO_2. The government has also imposed a requirement to evaluate CO_2 sequestration as an option for all new offshore oil and gas fields. The oil &

gas industry has set out an objective to reduce CO_2 emissions by 30 - 40% in the next 10 years.

Statoil is sequestering a million tonnes of CO_2 annually from North sea gas operations. Amine scrubbing is used for CO_2 collection. The CO_2 is liquefied and pumped downhole. Kværner is developing a membrane technology to absorb CO_2 into a liquid to improve the absorption process. If the membrane can work on both sides of the process, the energy consumption can be reduced by 40%. Pilot scale membrane tests are being carried out at commercial facilities.

There are 16 projects in various stages in Norway under a $70 million, 5-year program (Klimatek). Renewables including wind, hydro, and biomass are being promoted. The biphase turbine was noted as one device to be used in oil/gas mixtures to make power and product. Energy efficiency is also being studied as well as passive energy conservation. Ultimately some CO_2 must be recovered and stored. A plasma process is being studied for the production of carbon black and hydrogen. The carbon black can be used for hydrogen storage. This could be a means for using hydrogen to power automobiles.

Norsk Hydro is looking at a methane reformation process whereby CO_2 is scrubbed from the product gas. The hydrogen is mixed with additional methane to fire a gas turbine. The CO_2 is used in the oilfield for advanced oil recovery.

The third plenary session focused on *Terrestrial Sequestration.* The session was chaired by Roger Dahlman, Program Manager for Carbon Cycle Research, Office of Energy Research, DOE. He introduced the session by saying that of the 8.2 Gt (billion tonnes) of CO_2 that is produced from fossil fuels and land use change, 3.4 goes to the atmosphere and 2.0 goes to the ocean. The remaining 2.8 goes somewhere and, no doubt some of that goes back to the land and ocean margins. The mechanisms of exchange and fixation in these areas is important to the understanding how to manage the carbon cycle.

Professor Steven Wofsy of the Department of Atmospheric Sciences at Harvard University discussed *The Ameriflux Initiative and the Role of Forests as Sinks for* CO_2:

Forests are an important part of the global carbon system and an important resource. Large amounts of CO_2 can be potentially removed by forests (perhaps up to 25% of fossil fuel use). In addition, forests produce economic benefits while sequestering CO_2. However, forests are affected by climate change, pollution, nutrients, etc.

The scientific questions are: where is the CO_2 going?, why is it going there?, and can we control it? Measuring the trees is a problem. Wood measurements can be made, but much of the uptake is actually in the soil. Measurements can be taken of the air above the forests. A series of research sites have been set up to make these measurements in a project called AmeriFlux. At the moment, southern sites are taking up more CO_2 than northern sites. Enhanced understanding of the ongoing factors is crucial to managing the issue. Management strategies require long term focus as forests are long term in nature (over 100 years).

The next talk was by Keith Paustian of the Natural Resource Ecology Laboratory of Colorado State University, discussing the *Soil Sequestration of Carbon*.

> Soils constitute the largest terrestrial stock of organic C, on the order of 1200-1600 Pg (billion metric tonnes), roughly twice that contained in the worlds vegetation. Soils which have been or are used for agricultural purposes offer the greatest potential as a sink for atmospheric CO_2. Historically, agricultural uses have led to a depletion of the soil C in the native ecosystems from which they were derived, primarily through reduced C inputs (i.e. plant C is removed as a product rather than being returned directly to the soil) and through increased decomposition of soil organic matter due to tillage and other agricultural practices. Globally, it's estimated that around 50-60 Pg of organic C originally in soils have been lost due to the cultivation and conversion of forests, grasslands and wetlands to agriculture. However, improved management of agricultural soils can regain much of this lost C and thus provide a significant sink for atmospheric CO_2.
>
> Data from numerous long-term experiments show that adoption of no-till can increase soil C levels significantly, with most sites showing increases of 5 to 15 tonnes/hectare within a 10 to 30 year period. Similar and even higher rates of C accumulation are commonly found where annual cropland has been converted to perennial grasses, in set-asides or with pasture establishment. An extensive database on the effects of these and other practices is available from long-term experiments from around the world.
>
> The 1995 IPCC assessment estimates that there is a global potential for soil C sequestration on the order of 24-43 Pg, over a 50 year period, through the adoption of improved agricultural practices, use of set-asides and conservation buffers on marginal cropland and through restoration of degraded lands. A recent assessment of soil C sequestration potential in the US agriculture gives an estimate of 1.5 Pg over the next 20 years. The degree to which these levels are achievable are dependent on a variety of policy and economic factors. Measures to promote soil C storage provide a number of collateral benefits, such as improving soil fertility and soil quality as well as contributing to better air and water quality.

The next talk by Mark Trexler, President, Trexler and Associates, was on *Terrestrial Sequestration Policy Opportunities and Implementation Issues*:

> Deforestation currently emits 1.5 +/- 0.5 Gt/yr CO_2. Reducing the amount of deforestation has the potential to reduce emissions (as opposed to creating a sink).
>
> The potential for forestry is about 2 Gt/yr. However, the lost forests represent a lost opportunity. The fires is Mexico, Indonesia, and now in Florida represent lost forests with increased CO_2. Differences in interest groups have made it difficult to make progress in policy. The scale of the effort is important. The potential is recognized at the global and national scale, but becomes diffused at the project level. Offsets are being looked at across sectors and should not be considered synonymous with sinks. Setting up criteria that avoids gaming, produces real emissions reductions, and produces long term solutions is an extremely difficult task. In view of the previous presentation, if the forest is in an area that does little for the carbon balance, there should be no offset in principal. One problem is that economics

tend to be muddled. Benefits and costs are often calculated on different bases. Different discounts are used in different sectors and different areas.

A final talk in this session was given by Roger Sedjo of Resources for the Future on *Timber Supply and Forest Carbon in a World of Climate Change: Some Modeling Approaches and Results:*

A modeling framework was set up for timber supply. Added to that was an ecosystem model that looked at changes in growth and area distribution. Temperature and precipitation change impacts timber growth and, hence, supply. Global circulation models try to predict climate changes. The goal was originally to predict timber supply, but the model can be run in such a way as to look at the impact of forests on some of the other variables. One scenario that was analyzed looked at the demand for wood and its consequences for the forests and the carbon balance. Without management, the forests will increase to meet the wood demand and thus store more carbon. In addition, if the wood products are of the long lived variety (i.e., homes, furniture, wood paneling, etc.), there will be additional storage. If the forests are managed to maximize profits for the timber supply companies, perhaps up to 60% of the excess carbon can be accounted for. This assessment was quite a bit more optimistic regarding sequestration potential compared to the prior three presentations.

In the final plenary session before the breakout sessions began, Kelly Thambimuthu of National Resources Canada discussed *Opportunities for International Collaborative R&D*:

Dr. Thambimuthu is chairman of the IEA Greenhouse Gas R&D Program executive committee. There are 18 countries involved counting the EU as one country. There are also several companies as members including the three major oil companies. The objectives of the program are to evaluate different energy technologies for mitigating GHG impacts and to disseminate results. The studies include fossil fuels, CO_2 capture, storage, and utilization. Thus far, their conclusions are: capture is available, but expensive; storage is relatively inexpensive, but unproven; utilization is limited. Altogether, these techniques allow the continued use of current infrastructure. Whatever we do, it is necessary to think through from source to sink as far as various impacts are concerned.

One collaborative program involves the combustion of fossil fuels in and O_2/CO_2 (or enriched air) atmosphere. Flue gas will be mainly CO_2 (and thus easier to separate). An air separation plant provides the oxygen and recycled CO_2 provides the potential for temperature control. Product flue gas can be up to 98% CO_2. A one million Btu/hr combustor has been built and tested in Canada.

Another project looks at a coal bed sequestration approach. Basically, coal will absorb CO_2 at twice the level of methane. If the methane can be displaced by CO_2 in coal beds that are not mineable, methane can be recovered and used while CO_2 can be stored. The net storage of carbon increases as 2 moles of CO_2 are stored for 1 mole of methane.

The IEA is also involved with the Statoil project for injecting CO_2 into an aquifer. The projected dispersion of the CO_2 is 3 km from the injection point after 20 years. The IEA will provide the monitoring and measurement system for this program. Monitoring is expected to begin towards the end of this year.

In a project under the Climate Technology Initiative, the ocean sequestration of CO_2 is being evaluated. The CO_2 will be released at 1000 m depth off the coast of Hawaii. A ROV (remotely operated vehicle) will be used to monitor flow streams from the injection point.

Other opportunities for collaboration include monitoring CO_2 migration in EOR projects, monitoring CO_2 injection and migration in a land based aquifer, and hydrogen production.

The workshop then broke up into three parallel breakout sessions for the rest of day one and the morning of day 2. Each session was anchored with representatives from a key stakeholder industry -- coal, oil & gas, and electricity (utilities and equipment suppliers) -- and chaired by a representative of that industry. Each breakout was asked to address 4 topics:

- The role of carbon sequestration
- R&D priorities
- Possible industry-government-university partnerships
- The way forward

Summaries of each breakout session have been drafted and are currently being reviewed by the participants. They will appear in a workshop proceedings scheduled for release in August, 1998. Copies of the visuals used by the plenary speakers will also be included in the proceedings.

In the evening of day 1, Morris Adelman, Professor Emeritus of Economics at MIT gave a dinner speech on *The Future of Fossil Energy*. Some of his comments included:

The key question is not what are the reserves, but rather what is the cost of getting the resource. If the extraction costs are going up, then the commodity cost will increase. In essence, these resources never run out, they just become too expensive to recover. If the cost is going down, as has been the case for energy in recent years, then there will be no shortages and stable prices. After citing many examples to support his thesis, Prof. Adelman concluded his talk by saying we will *not* solve the problem of climate change by running out of fossil fuels.

After lunch on day 2, the breakout session chairs reported on their sessions to the plenary. The meeting was then closed by Charles Schmidt, Office of Power Systems, FETC. He thanked all attendees for taking time from their busy schedules to participate in the workshop. The results of this workshop will be used as input to a meeting of representatives from the various government agencies to coordinate their efforts in carbon sequestration. That meeting will be held on July 23-24, 1998 in Morgantown, WV.

Acknowledgment

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AGENDA

Stakeholders' Workshop on Carbon Sequestration
Massachusetts Institute of Technology
Cambridge, MA
June 22-23, 1998

Monday, June 22, 1998

8:00 Registration and Continental Breakfast
E51, Tang Building, 1st floor

9:00 Plenary Session I - Opening Session
Chair: Jefferson Tester, Director, MIT Energy Laboratory

Welcoming Remarks

Keynote Address
Rita Bajura, Director, Federal Energy Technology Center

Technology's Role in Carbon Management
Henry (Jake) Jacoby, William F Pounds Professor of Management, MIT

10:30 Break

11:00 Plenary Session II - Sequestration Technologies
Chair: Elisabeth Drake, Associate Director, MIT Energy Laboratory

Overview of Technologies for CO_2 Sequestration
Howard Herzog, Principal Research Engineer, MIT

The Technological Response in Norway
Olav Falk-Pedersen, Kvaerner Oil & Gas

12:15 Lunch

1:30 Plenary Session III - Terrestrial Sequestration
Chair: Roger Dahlman, Program Manager for Carbon Cycle Research, Office of Energy Research, US Department of Energy

The Ameriflux Initiative and the Role of Forests as Sinks for CO_2
Steven Wofsy, Professor, Department of Atmospheric Sciences, Harvard University

Soil Sequestration of Carbon
Keith Paustian, Research Scientist, Natural Resource Ecology Laboratory, Colorado State University

Terrestrial Sequestration Policy Opportunities and Implementation Issues
Mark Trexler, President, Trexler and Associates, Inc.

3:00 Break

3:30 Plenary Session IV - International Outlook
Chair: Perry Bergman, Federal Energy Technology Center

Opportunities for International Collaborative R&D
Kelly Thambimuthu, Natural Resources Canada

4:00 Charge to Breakout Sessions

4:15 Breakout Session I
Coal Breakout Chair: John Wootten, Vice President, Peabody Group

Electricity Breakout Chair: Rodger McKain, Vice President R&D, McDermott Technology

Oil & Gas Breakout Chair: Michael Wilkinson, Technology Consultant, BP Exploration

5:30 Adjournment

6:30 Reception
Marriott Cambridge Hotel, 2nd Floor Foyer

7:30 Dinner
Marriott Cambridge Hotel, Salon III

8:30 The Future of Fossil Energy
Morris Adelman, Professor Emeritus of Economics, MIT

9:15 Adjournment

Tuesday, June 23, 1998

8:00 Continental Breakfast

8:45 Feedback from initial breakout sessions -- resolution of questions or issues that arose

9:00 Breakout Session II

12:15 Lunch

1:30 Plenary Session V - Wrap-up
Reports from breakout sessions

Concluding Remarks

2:30 Adjournment

AGENDA FOR BREAKOUT SESSIONS

The purpose of the breakout sessions are to get feedback from you, the stakeholders. We have divided the participants by industry group: coal, electricity, and oil & gas. Assigned to each breakout session will be a representative of the stakeholders to chair the session, a facilitator to help keep the discussions focused, and a rapporteur to take notes of the deliberations. There will be no attribution to any individual or company of statements made. A summary of each breakout session will be presented in the final plenary session of the workshop. A written summary will also be prepared for inclusion in the workshop proceedings. Members of each breakout group will be given a chance to comment on the written summary prior to publication.

The breakout groups should address the four topics described below and develop the requested products for the last three topics. The suggested questions are meant to offer guidance in your discussions. Each breakout session should feel free to modify the agenda as you see fit.

1. **The role of carbon sequestration.**

    - What carbon sequestration and related enabling technologies do you feel could be important in the near- to mid-term (<2020)? in the longer-term (>2020)? Do not limit yourselves to technologies mentioned in the plenary sessions.

    - What types of preparation are needed for carbon sequestration to be cost-effective and publicly accepted? Do we need a concerted national effort? If so, what might that be?

2. **R&D priorities.**
    Desired outcome/product: A list of prioritized research topics of interest to you. Indicate where you believe the government should participate.

    - What is your industry's time frame of interest for R&D investment in general? for sequestration R&D?

    - What carbon sequestration and/or enabling technologies appear to be most relevant to your company? What technologies do not seem so relevant or high priority?

    - From the viewpoint of your company or industry, what do you consider the highest priority challenges to address in carbon sequestration? Note, these need not be limited to technical challenges. For example, how important are issues related to public acceptance and can we do research to help address these concerns?

3. **Possible industry-government-university partnerships.**
    Desired outcome/product: A list of suggestions of ways for industry/government/universities to collaborate/partner. These may be new ideas on how to work together, as well as examples of things that have worked well in the past or present. Please include specific goals, potential participants, and time frames of interest.

    - In developing carbon sequestration technologies, what do you view as the appropriate role for industry? for government? for universities?

- What are ways to establish and maintain a dialog among interested researchers? What other groups are important to include in this dialog?

- Do you have any specific suggestions for approaches to form partnerships?

4. The way forward.
Desired outcome/product: Suggestions for some specific next steps. Highlight the 3-5 highest priority items.

- Are our decision makers well informed about the carbon sequestration option? What about the general public? If not well informed, how can we address this?

- It has been proposed to follow-up this workshop with smaller, more focussed workshops based on areas of interest identified here. These subsequent workshops would focus on more detailed discussions of how to move forward. Then, we might gather back together again in about a year's time to do a "lessons learned" review. What is your opinion of this plan? What topics would you want to be addressed by the follow-up meetings? What other options should be considered?

- Are there other ways to keep stakeholders informed and to solicit their input and participation?

- What would you suggest as the next step in this process?